

B-Factory Constraints on Low-Mass Dark Matter

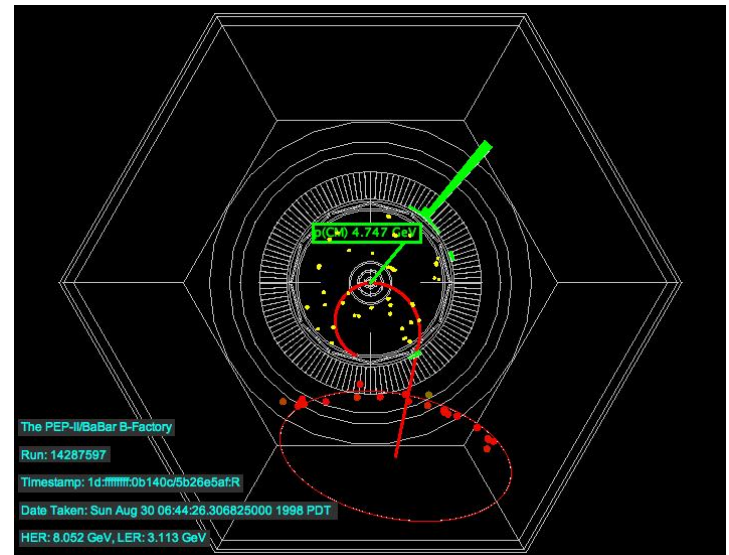
Yury Kolomensky

LBNL/UC Berkeley

For the BABAR Collaboration

TAUP 2013

September 11, 2013



Direct Searches for Low-Mass New Physics

- Models inspired by astrophysical and astro-particle observations
 - Strongest hint: INTEGRAL 511 keV anomaly
 - Also positron, γ -ray excess in PAMELA, FERMI
 - Hints of low-mass direct DM detection (DAMA, CoGeNT, CRESST)
- ☞ Typical models: low-mass (<10 GeV) gauge bosons and/or scalars (Higgs)

A puzzle in the center of the galaxy

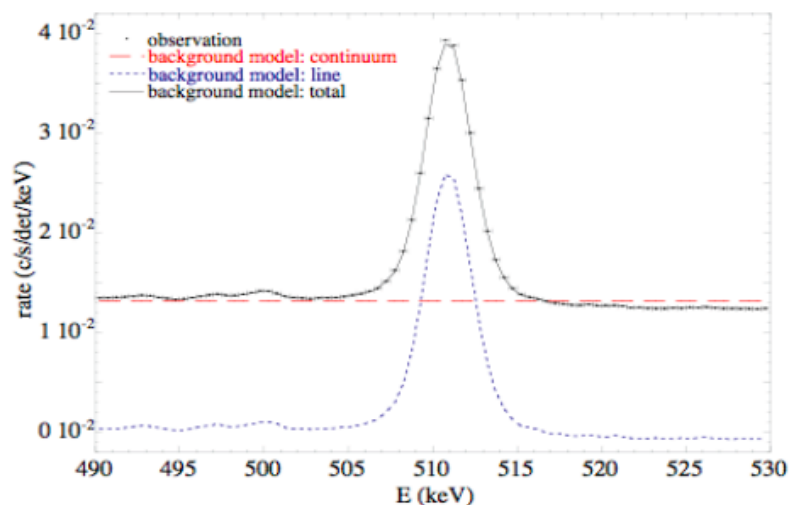
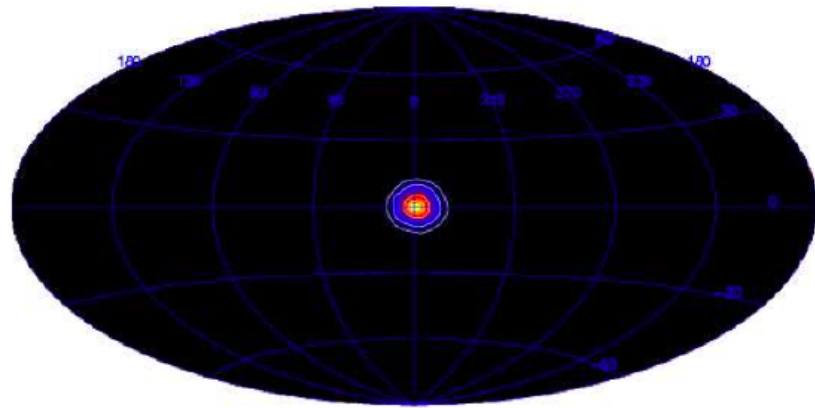


Fig. 1. Raw spectrum and background model components.

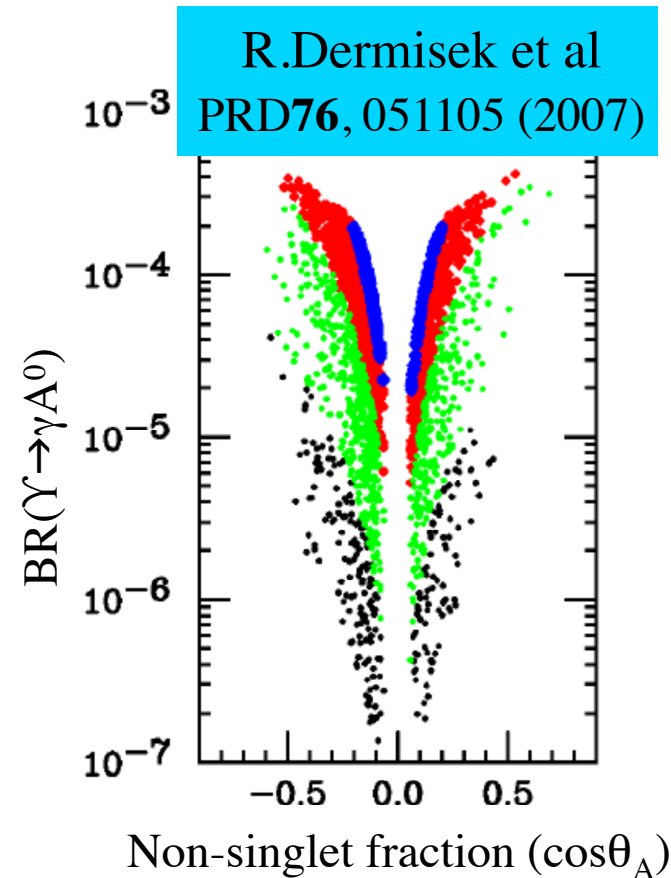
INTEGRAL source



- Not consistent with point source
 - (needed 7 in 1yr data)
- Courtesy N. Weiner

Examples

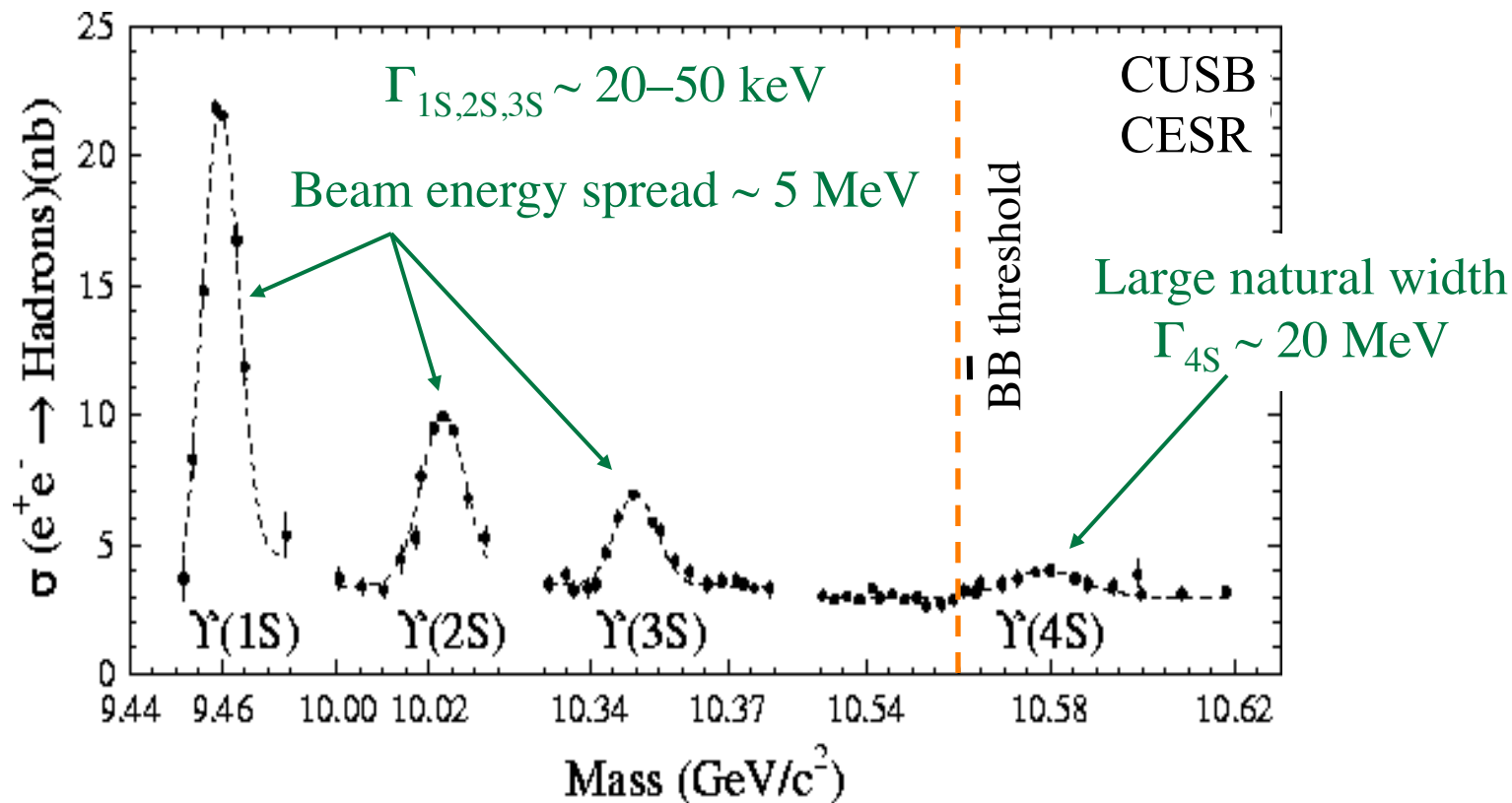
- Models with low-mass dark matter and/or gauge bosons
 - ☞ E.g. “Dark Sector”
- NMSSM models with light CP-odd Higgs
 - ☐ Solve fine-tuning problems in MSSM
 - ☐ CP-odd Higgs, A^0 , below $2m_b$ is not constrained by LEP
 - ☞ Large BR for $\Upsilon \rightarrow \gamma A^0$ possible
- Accessible at B-Factories in e^+e^- annihilation or bottomonium decays
 - ☐ Subject of a comprehensive campaign of searches in BaBar since 2008
 - ☞ 7 publications, 2 prelim. results, several ongoing analyses



$$\begin{aligned}
 &m_{A^0} < 2m_\tau \\
 &2m_\tau < m_{A^0} < 7.5 \text{ GeV} \\
 &7.5 \text{ GeV} < m_{A^0} < 8.8 \text{ GeV} \\
 &8.8 \text{ GeV} < m_{A^0} < 9.2 \text{ GeV}
 \end{aligned}$$

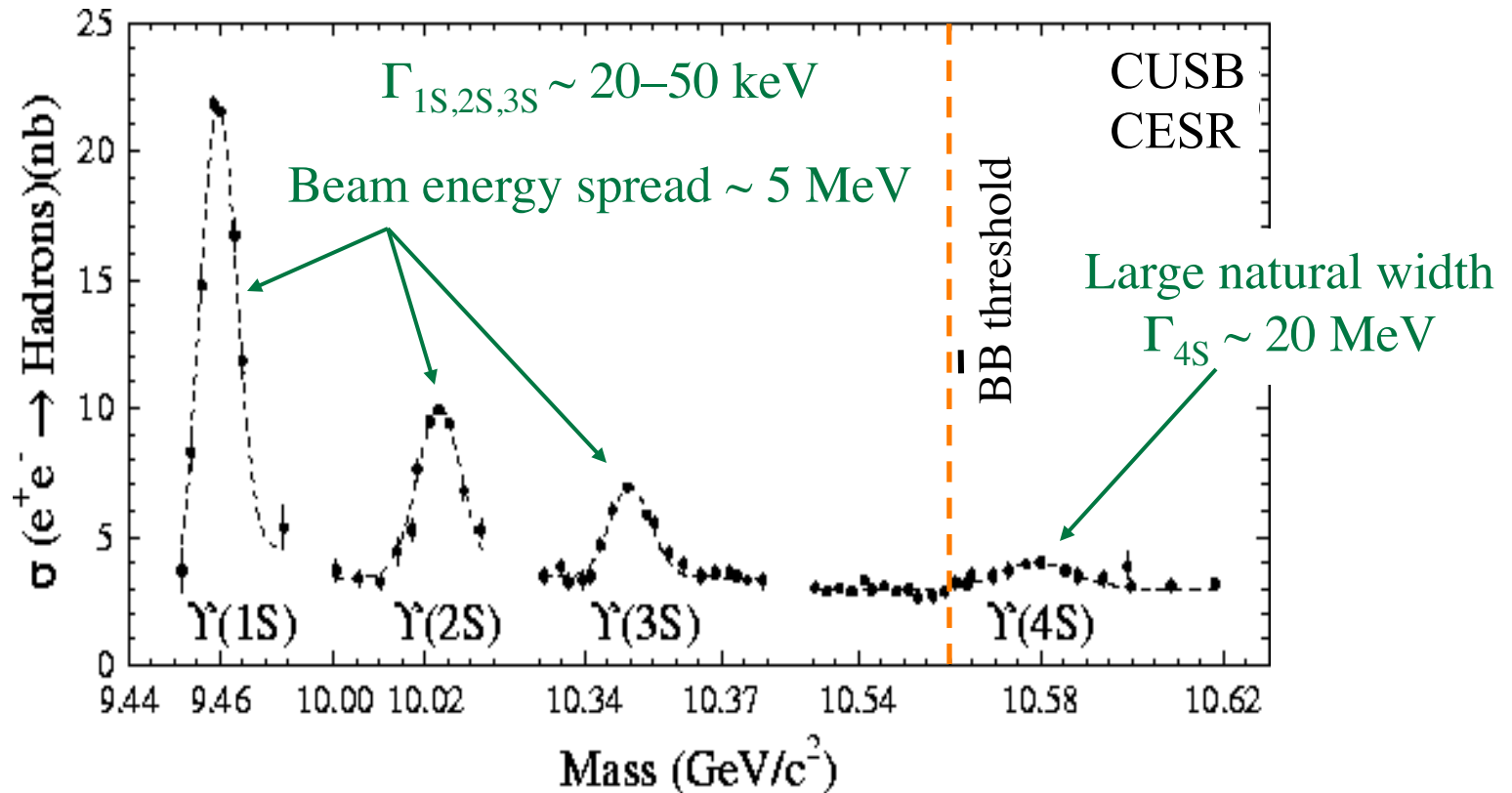
Upsilon Resonances

- Electron-Positron collider: $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS)$



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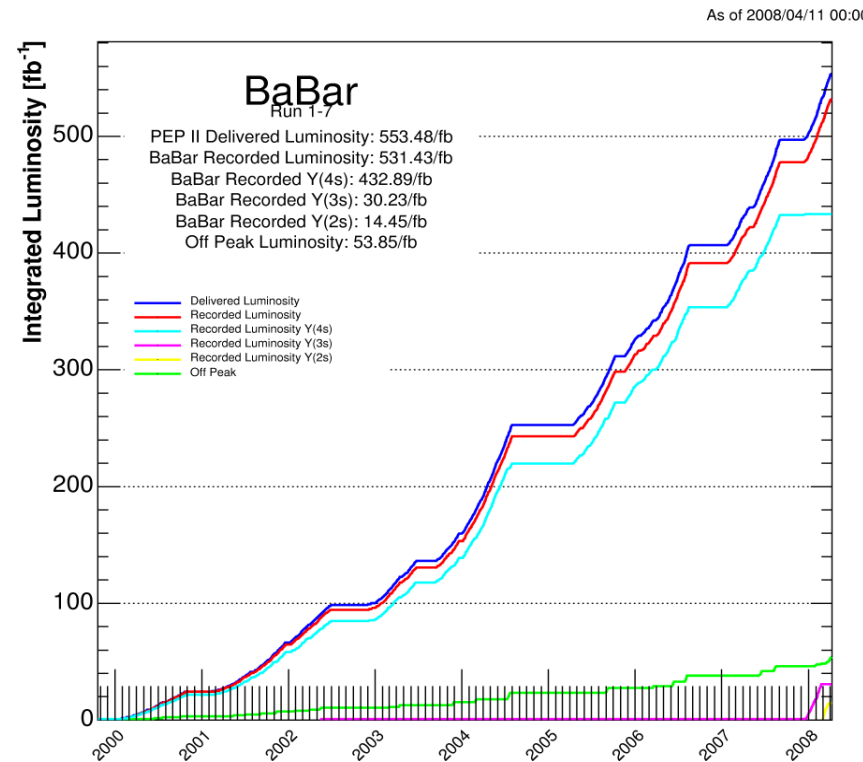
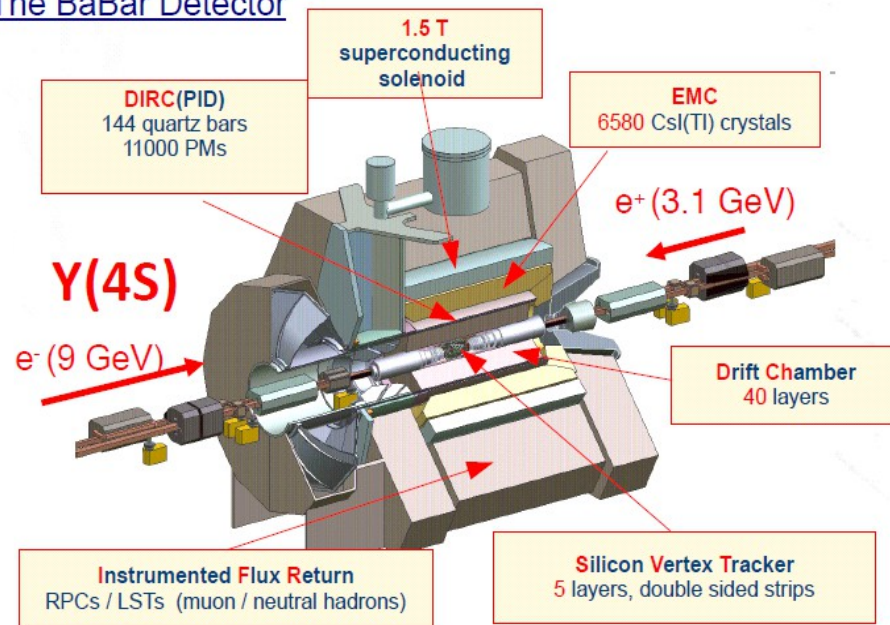
For any bottomonium process $BF_{nS} = \Gamma_{nS}/\Gamma_{\text{tot}} \gg BF_{4S}$, $n=1,2,3$

Significantly better sensitivity to direct production of light degrees of freedom @ narrow resonances. **Focus of BaBar's Run7 (2008)**

BaBar Experiment

~3 mwe overburden

The BaBar Detector



BaBar dataset: ~520 fb⁻¹ total collected luminosity

~470M $\Upsilon(4S)$ decays

~120M $\Upsilon(3S)$ decays

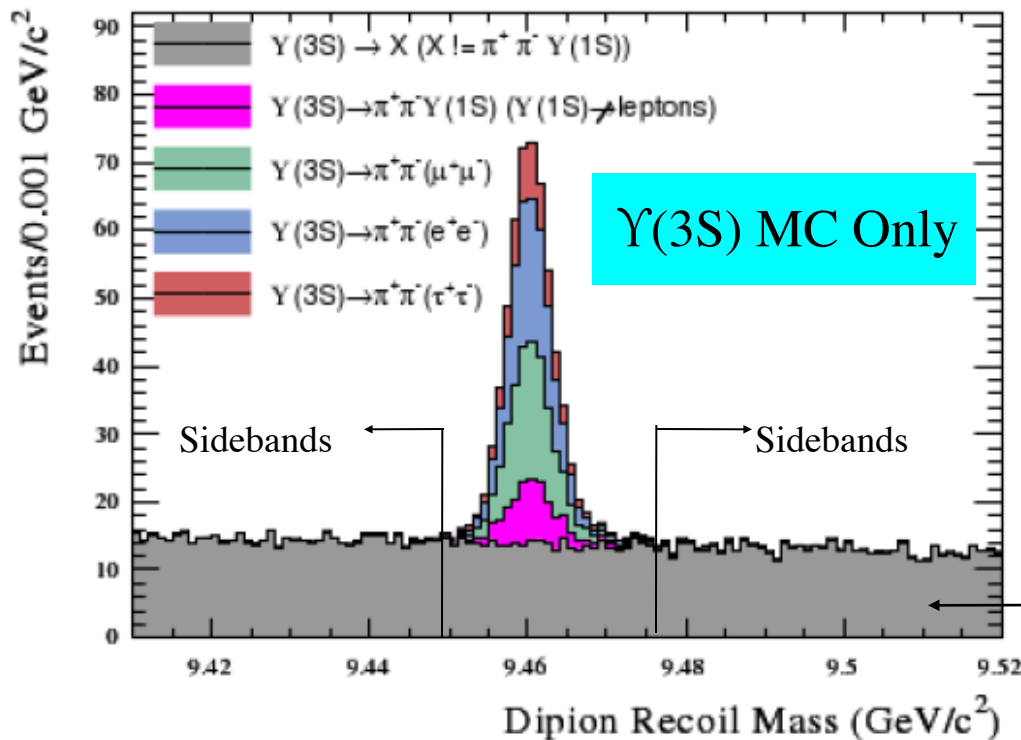
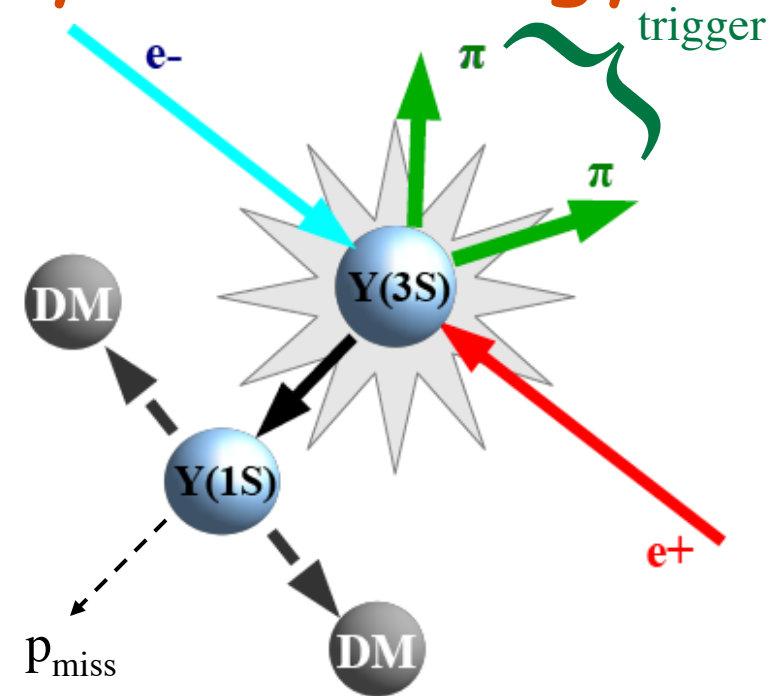
~100M $\Upsilon(2S)$ decays

Searches for Dark Matter Production

- Generic model: DM particle χ with $m_\chi < m_Y/2$
 - Plus a new scalar (A^0) or vector (A') particle to mediate s-channel annihilation
 - ☞ On-shell: $m_\chi < m_A/2 < m_Y/2$: resonant decays of Y
 - ☞ Off-shell ($m_\chi < m_Y/2 < m_A/2$): non-resonant decays
- Signatures and predicted rates:
 - Invisible decays of Y with $\text{BF} \gg \text{BF}(Y \rightarrow \nu\nu)$
 - ☞ $\text{BF}(Y \rightarrow \chi\chi) \sim 4 \times 10^{-4} - 2 \times 10^{-3}$ [McElrath, PRD **72**, 103508 (2005)]
 - Radiative decays $Y \rightarrow \gamma + \text{invisible}$
 - ☞ $\text{BF}(Y \rightarrow \gamma\chi\chi) \sim 10^{-5} - 10^{-4}$ [Yeghiyan, PRD **80**, 115019 (2009)]

$\Upsilon(1S) \rightarrow \text{invisible}$: Analysis Strategy

Leverage the charged dipion transition to the $\Upsilon(1S)$ (4.48%) to suppress background



$$m_{\text{recoil}}^2 = s + m_{\pi\pi}^2 - 2 E_{\pi\pi} \sqrt{s}$$

Additional non-peaking backgrounds from $e^+e^- \rightarrow \gamma^* \gamma^* \rightarrow e^+e^- \pi^+ \pi^-$ not included

$\Upsilon(1S) \rightarrow \text{invisible}$: Signal Extraction

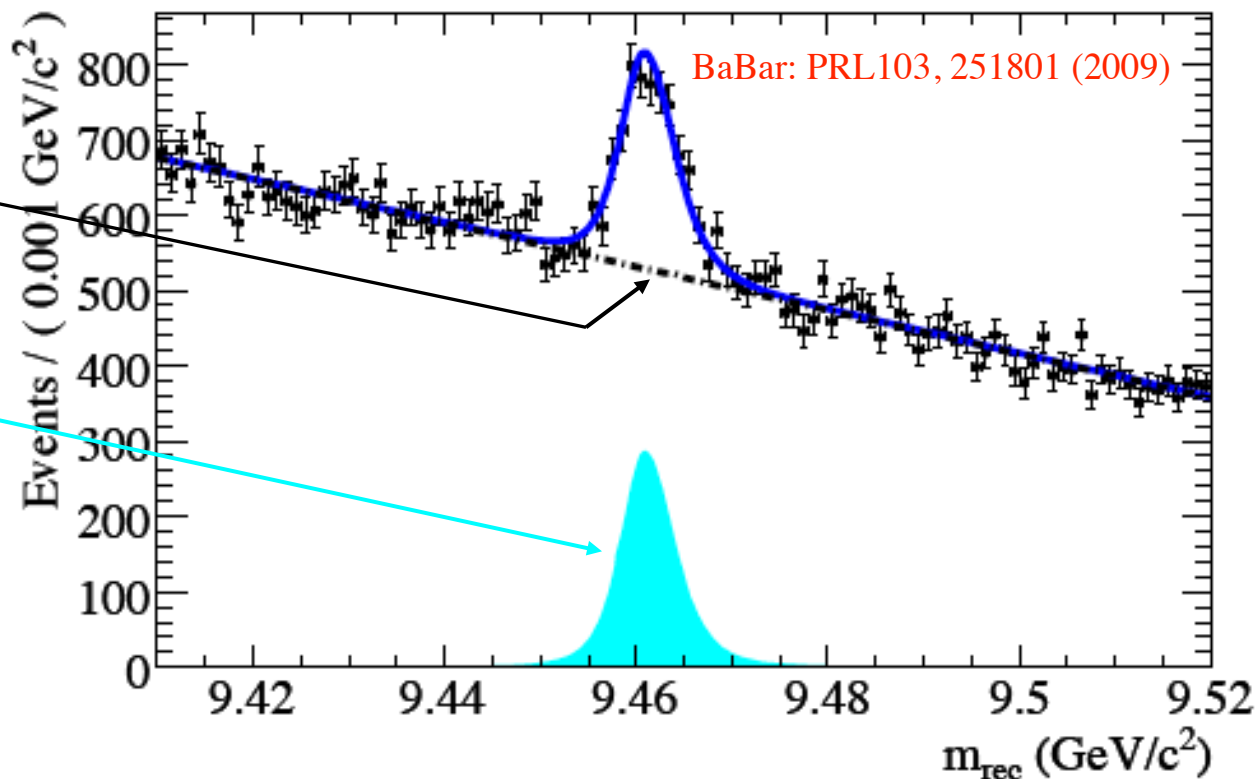
Maximum likelihood fit to
2-track “invisible” sample

Non-peaking background:

✓ Float all parameters and
yield

Peaking Component:

✓ Fix shape, float yield
Contains peaking
background and signal



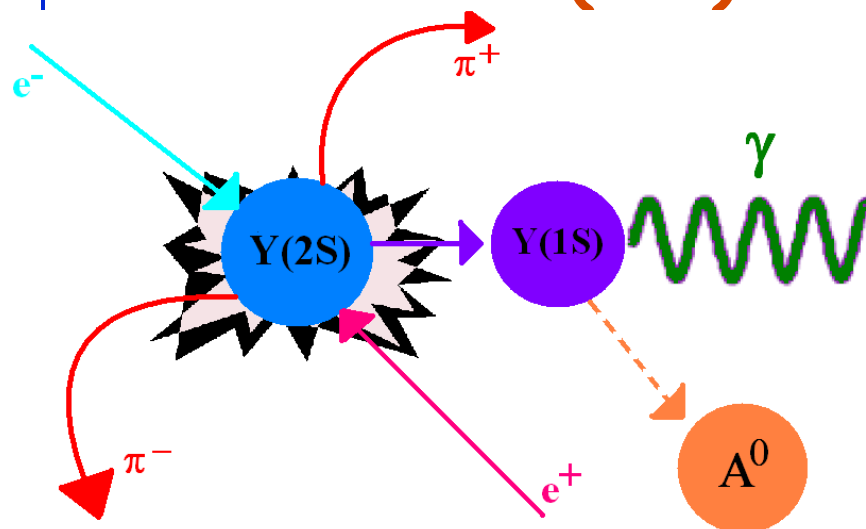
$$\text{BR}(\Upsilon(1S) \rightarrow \text{invisible}) = [-1.6 \pm 1.4 \text{ (stat.)} \pm 1.6 \text{ (syst.)}] \times 10^{-4}$$

$$\text{BR}(\Upsilon(1S) \rightarrow \text{invisible}) < 3.0 \times 10^{-4} \text{ @ 90\% C.L. [BaBar PRL103, 251801 (2009)]}$$

$$\text{BR}(\Upsilon(1S) \rightarrow \text{invisible}) < 2.5 \times 10^{-3} \text{ @ 90\% C.L. [Belle PRL98, 132001 (2007)]}$$

→ Strong constraint on models with DM below 4.5 GeV

$\Upsilon(1S) \rightarrow \gamma + \text{invisible}$



Search for decay chain $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$,
 $\Upsilon(1S) \rightarrow \gamma + \text{invisible}$

Resonant (invisible=Higgs) or non-resonant
(invisible= $\chi\chi$, e.g. light dark matter)

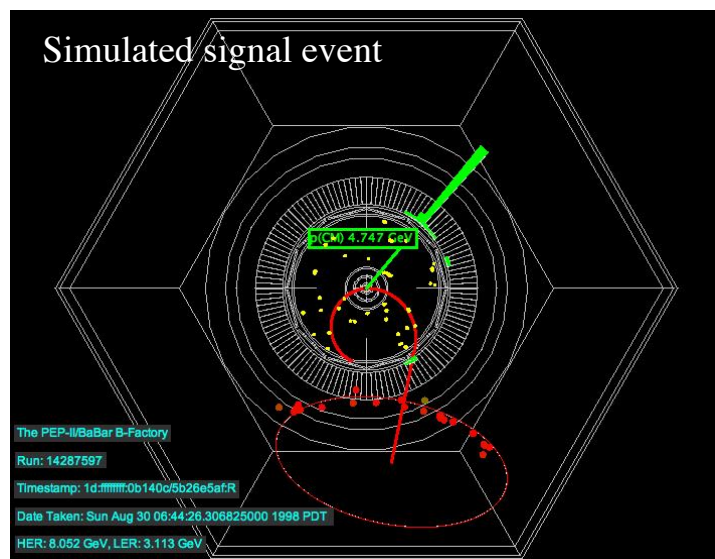
Identify the event by two low-momentum
pions from $\Upsilon(1S) \rightarrow \pi^+ \pi^-$ transition, a single
energetic photon, and large missing energy

Two key kinematic variables: missing mass
 M_X^2 , and dipion recoil mass

$$E_\gamma^* = \frac{M_{\Upsilon(1S)}^2 - M_X^2}{2M_{\Upsilon(1S)}}$$

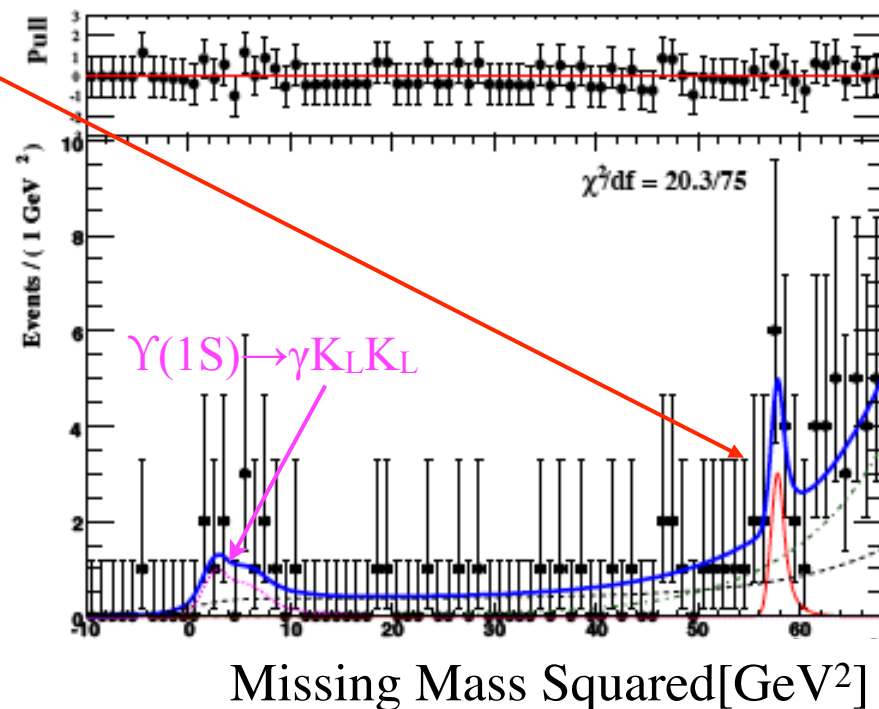
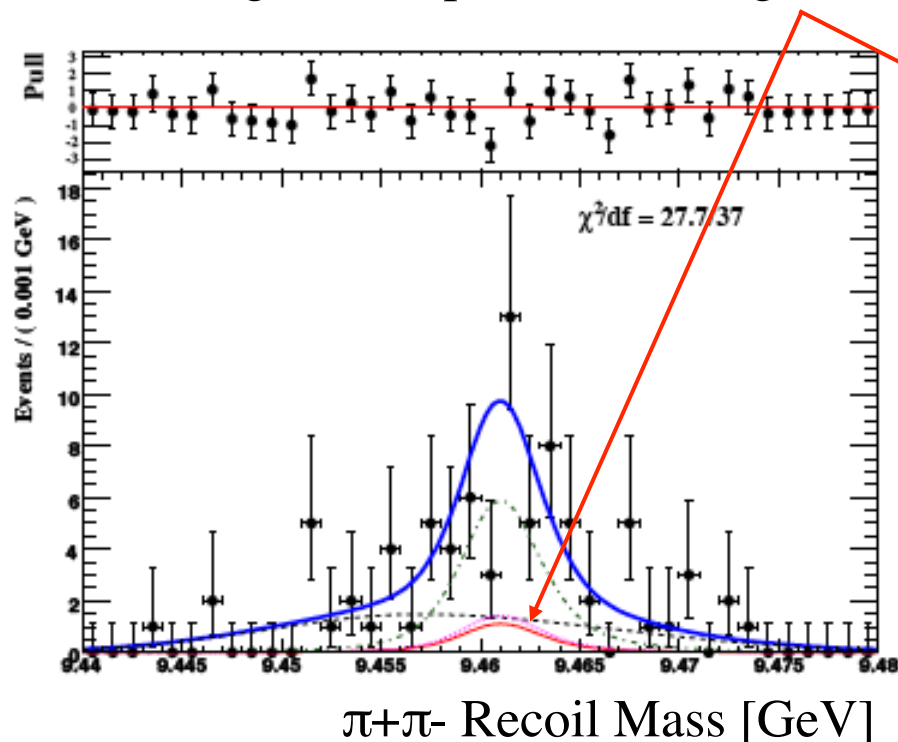
$$m_{recoil}^2 = s + m_{\pi\pi}^2 - 2\sqrt{s}E_{\pi\pi}$$

Search for excess of events over background
as a function of missing mass



Example: $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \text{invisible}$

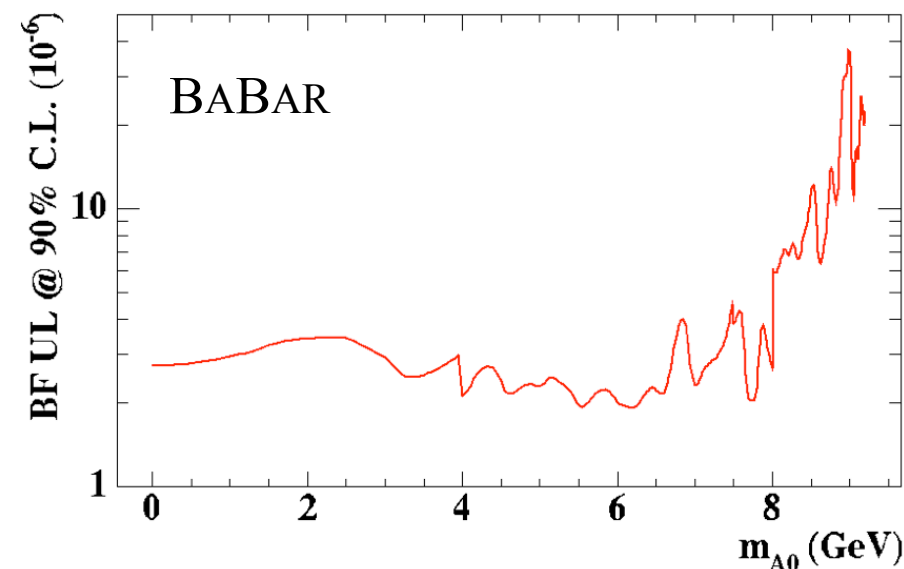
Most significant peak in missing mass: $m_{A^0} = 7.58 \text{ GeV}$, 2.0σ significance



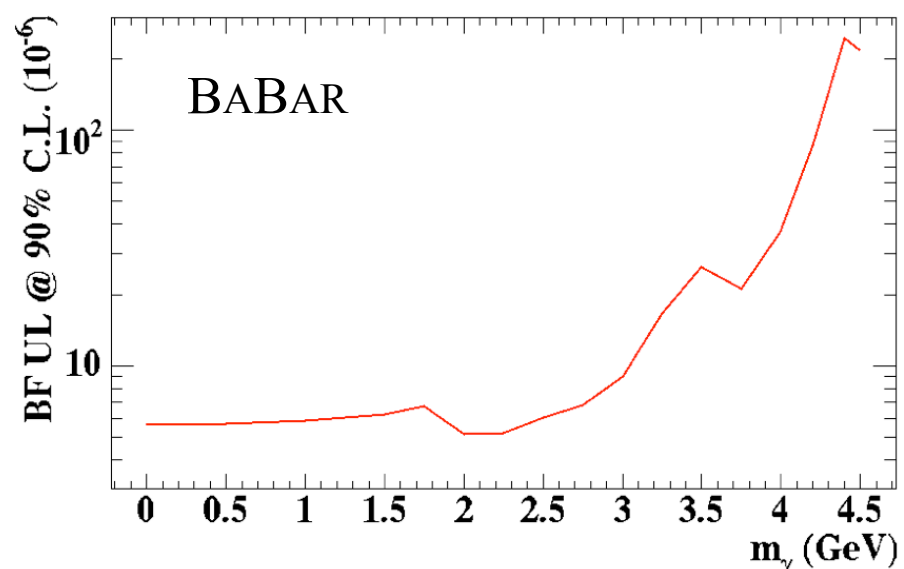
>30% probability to observe a peak of this significance *anywhere* in $m_{A^0} < 9.2 \text{ GeV}$ range

PRL **107**, 021804 (2011)

$\Upsilon(1S) \rightarrow \gamma + \text{invisible}$ Limits



Resonant $\Upsilon(1S) \rightarrow \gamma A^0$ search



Non-resonant $\Upsilon(1S) \rightarrow \gamma \chi \chi$ search

Best limits on radiative decays of $\Upsilon(1S)$ to invisible final states

PRL **107**, 021804 (2011)

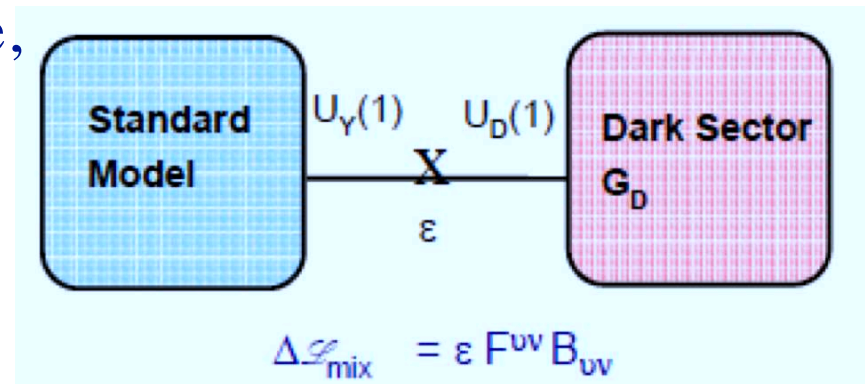
Gauge Bosons in the "Dark Sector"

Dark matter particles in $\sim \text{TeV}$ range,
but new gauge bosons in $\sim \text{GeV}$
range

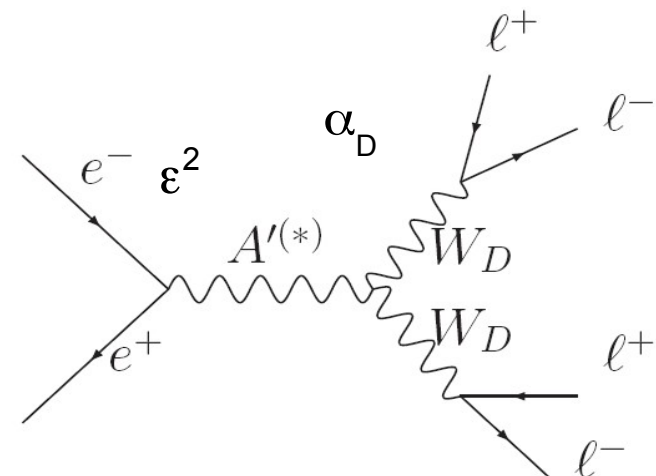
Coupling to leptons due to small
mixing between SM and DS

New gauge bosons decay to lepton
pairs, anti-proton production
forbidden by kinematics or
suppressed \rightarrow explains PAMELA/
ATIC features

Search for low-mass states in e^+e^-
annihilation @ B-Factories



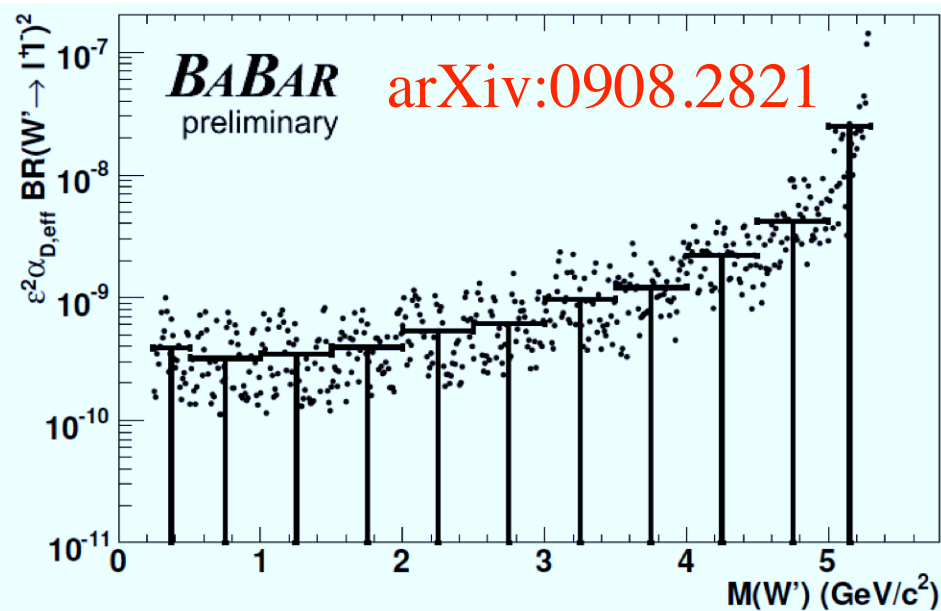
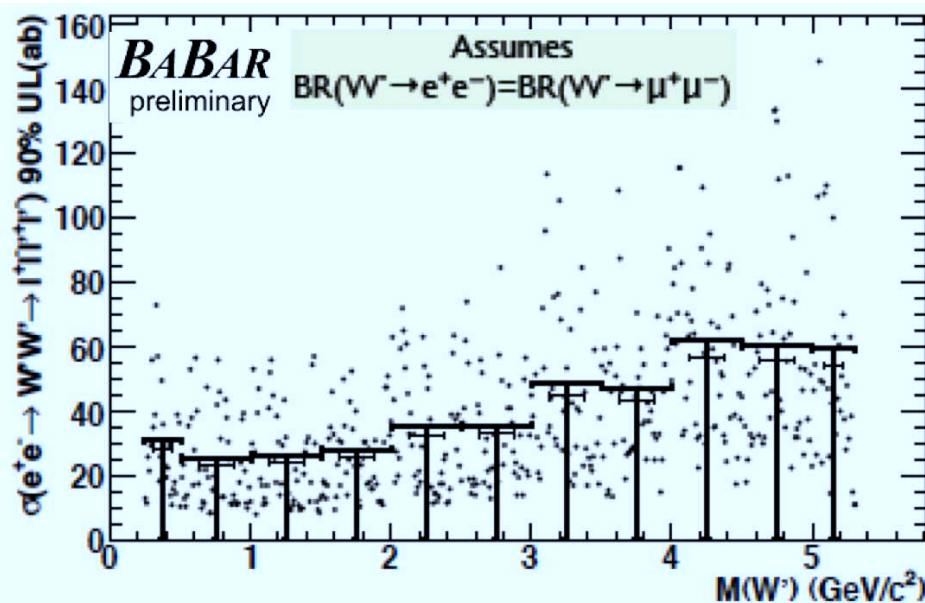
N. Arkani-Hamed et al
PRD 79, 015014 (2009)



Direct Search for Dark Sector

Look for $e^+e^- \rightarrow l^+l^-l'^+l'^-$ final states ($4e, 2e2\mu, 4\mu$) as a function of two-lepton mass

Full BaBar dataset ($\sim 540 \text{ fb}^{-1}$)



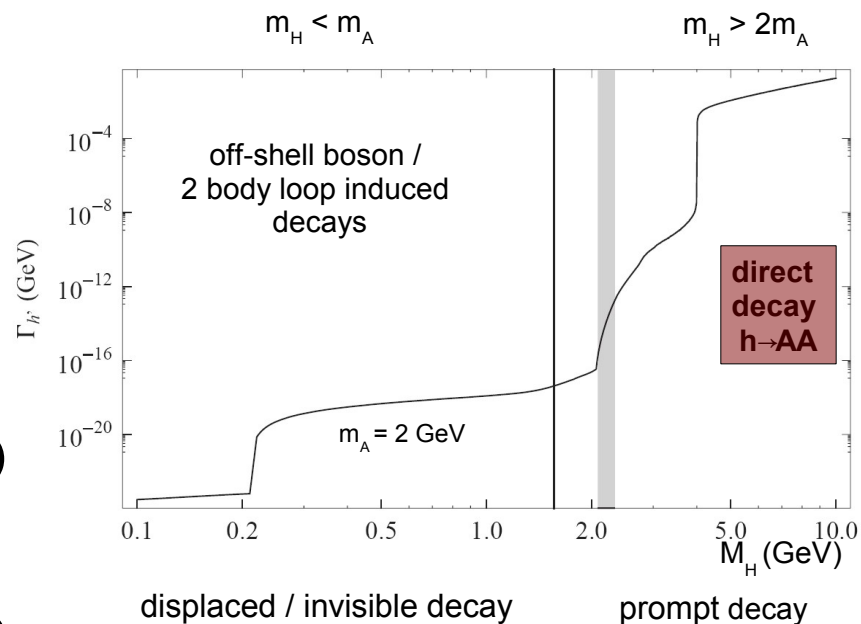
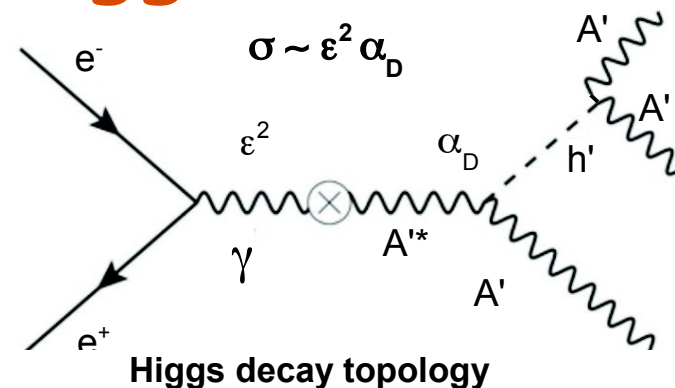
$$\sigma(e^+e^- \rightarrow W'W' \rightarrow l^+l^-l'^+l'^-) < (25 - 60) \text{ ab}$$

Some of the smallest cross section ULs measured @ B-Factories

Search for Dark Higgs

- Extension of the dark sector models: dark Higgs

- Mass generation in dark sector
- Mass can be low
- Detect by Higgs-strahlung process $e^+e^- \rightarrow A'h'$
- Decays to A' pairs
 - ☞ Multi-particle (multi-lepton) final state
 - ☞ Clean detection, virtually no QED background



Dark Higgs Search

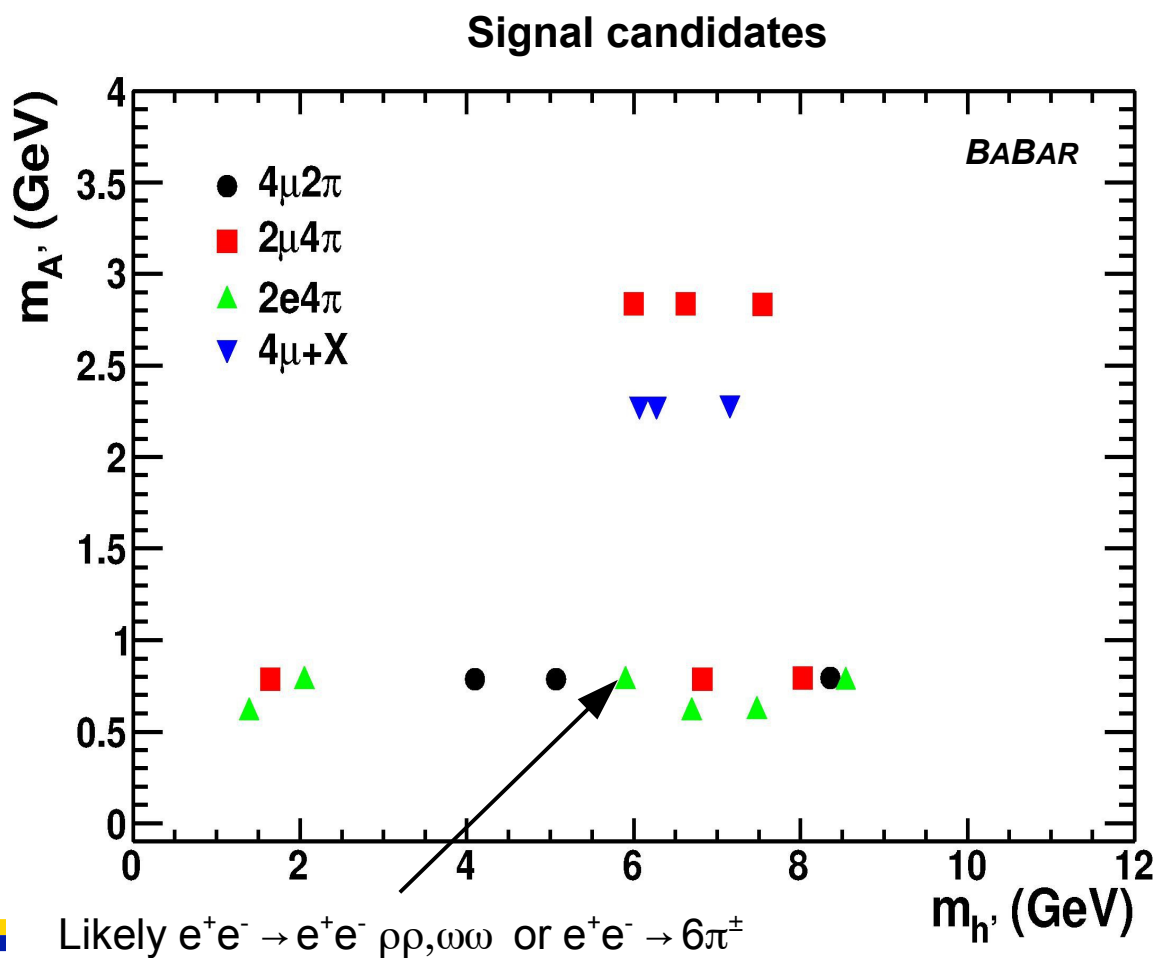
Focus on direct decay topology: $e^+e^- \rightarrow A'h'$; $h' \rightarrow A'A'$

Look for A' decays to a pair of oppositely-charged tracks, or to invisible final state ($A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, X$)

Require same mass for each pair

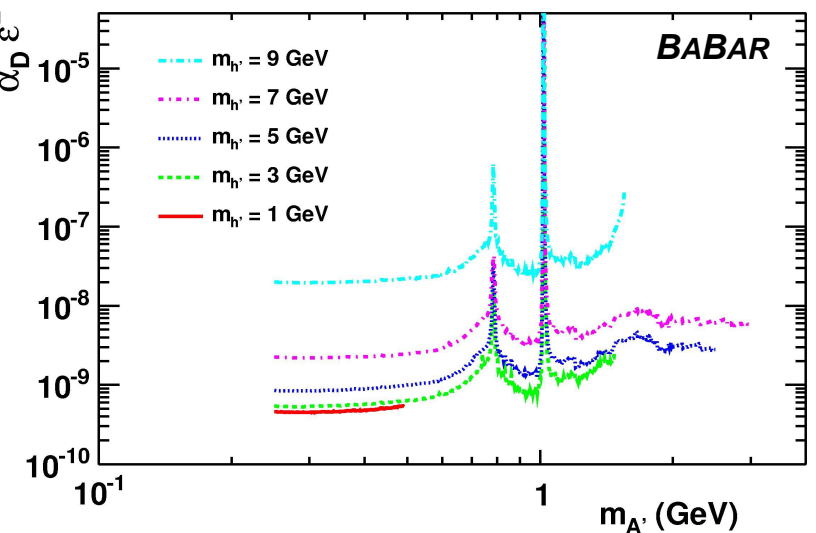
6 events selected
(18 combinations)

Consistent with
background estimates

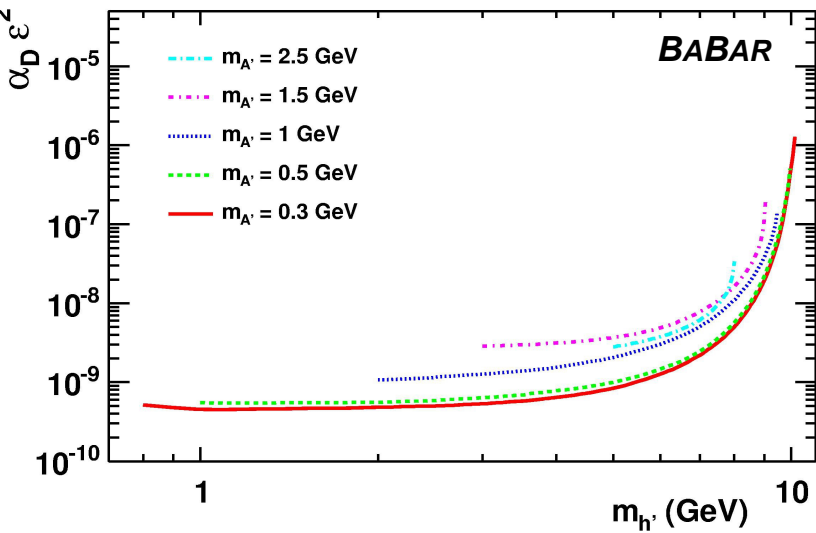


Dark Higgs Limits

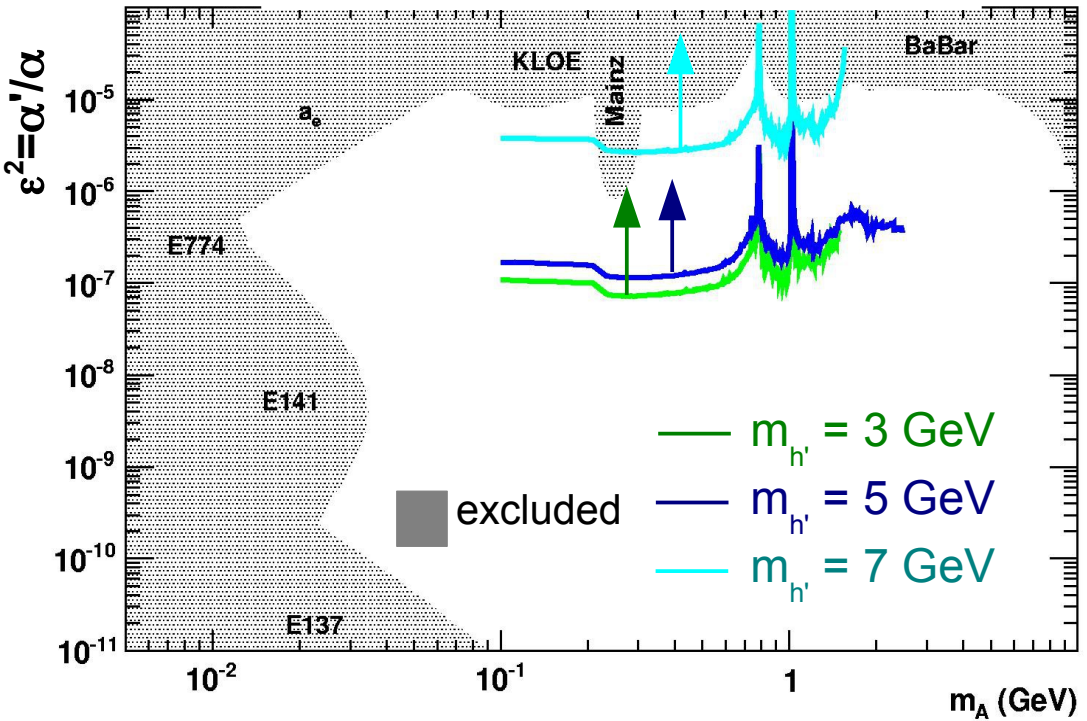
90% CL upper limit on $\alpha_D \epsilon^2$



90% CL upper limit on $\alpha_D \epsilon^2$



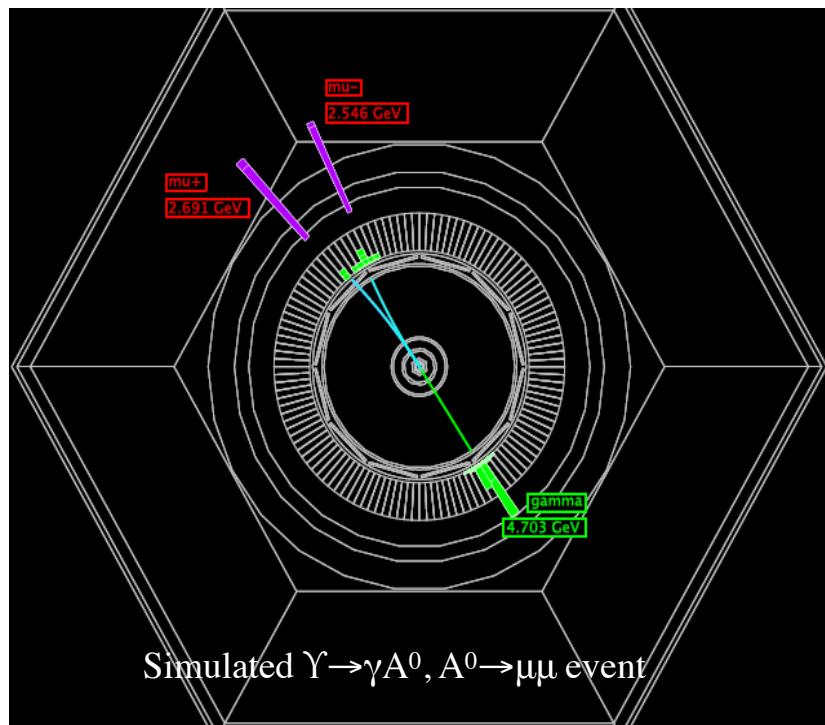
Limit on $\epsilon^2 = \alpha'/\alpha$ assuming $\alpha_D = \alpha_{em} = 1/137$



PRL 108, 211801 (2012)

Substantial improvement over previous limits. Constrain model space

Higgs Searches: $e^+e^- \rightarrow \Upsilon(2S,3S) \rightarrow \gamma A^0$

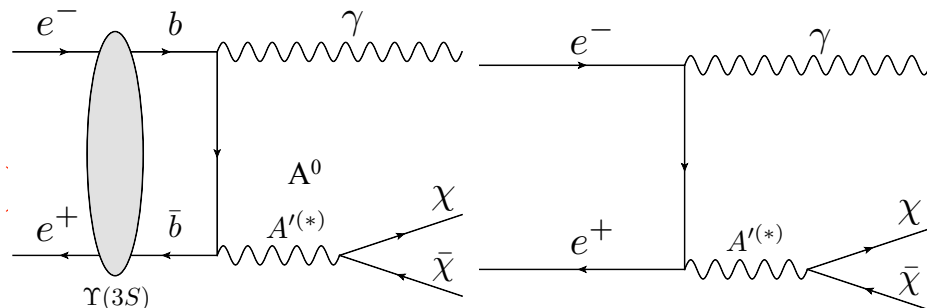


- (Pseudo)scalar $A^0 \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$, hadrons
- Partially or fully-reconstructed final state: ≥ 2 charged tracks, 1 photon

Look for A^0 decays as a narrow peak in photon energy or A^0 invariant mass

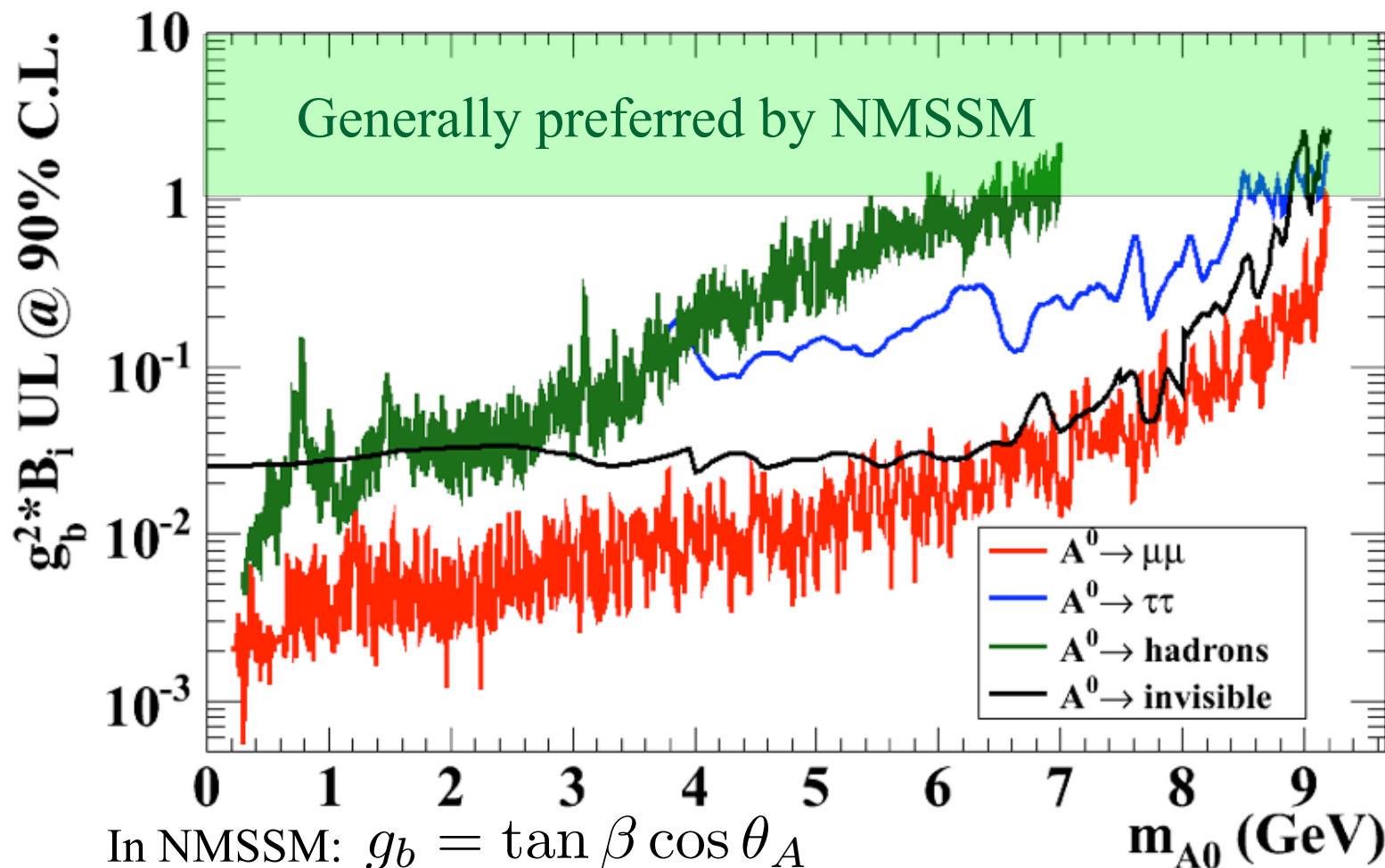
Also can be interpreted as search for a vector gauge boson (“dark photon”) in $e^+e^- \rightarrow \gamma A'$

- ✓ $A^0 \rightarrow \mu^+\mu^-$, PRL103, 081803 (2009)
- ✓ $A^0 \rightarrow \tau^+\tau^-$, PRL103, 181801 (2009)
- ✓ $A^0 \rightarrow \text{hadrons}$, PRL107, 221803 (2011)
- ✓ $A^0 \rightarrow \text{invisible}$, arXiv:0808.0017



Diagrams courtesy R. Essig et al.

BABAR Higgs Coupling Limits

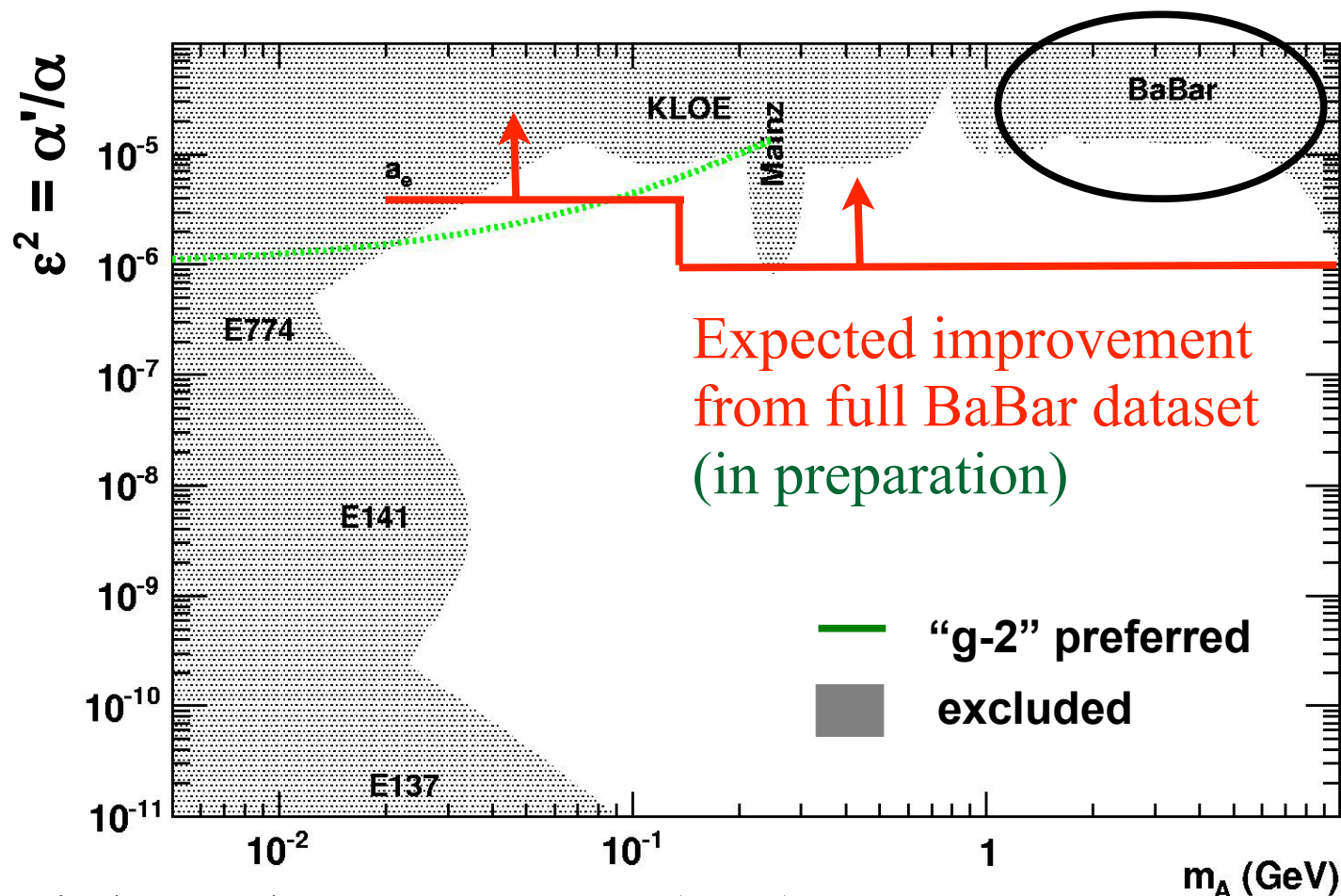


Comprehensive limits on low-mass (NMSSM etc.) Higgs

Also place significant constraints on other models, e.g. axion-like states, dark photons

Dark Photon Limits

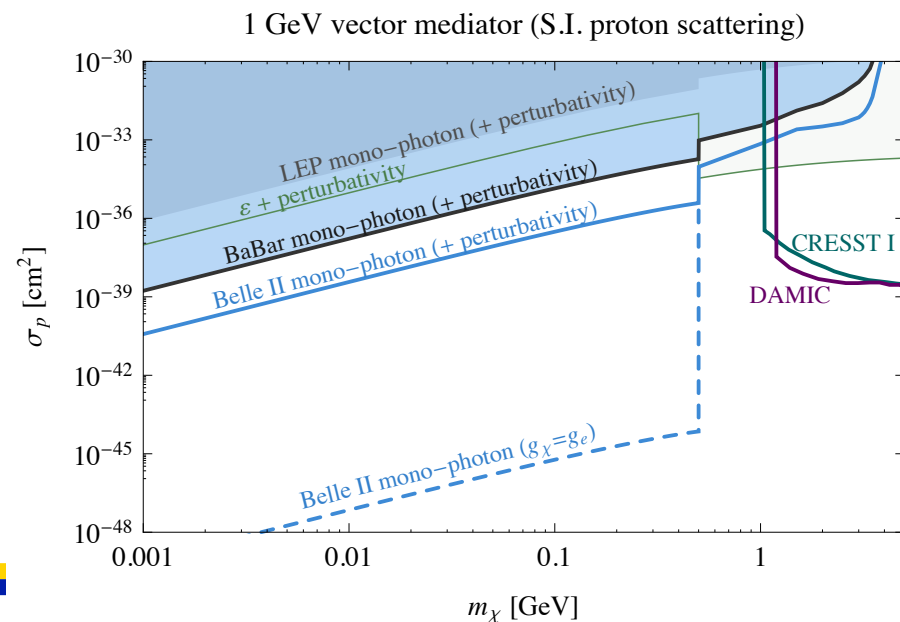
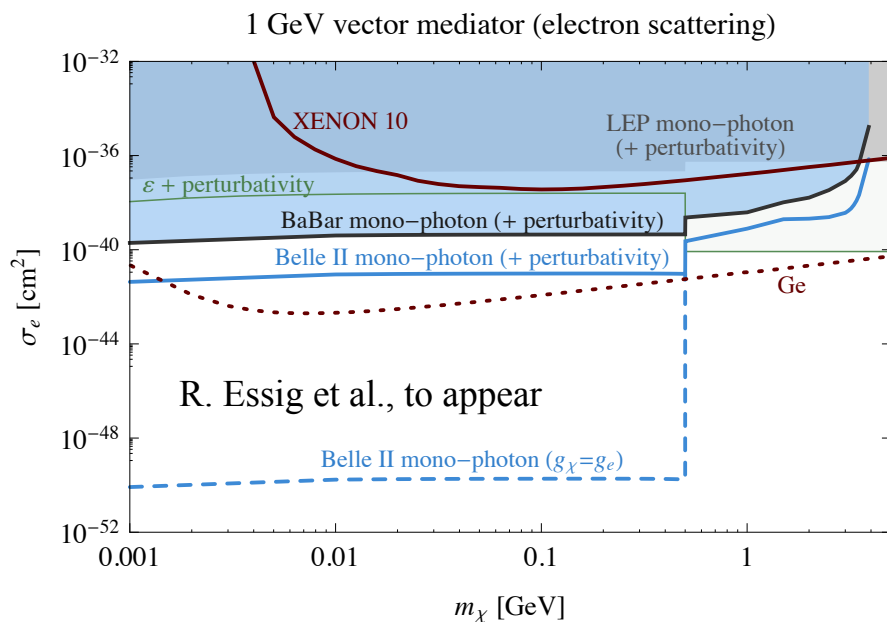
Limit obtained by reinterpreting the $Y(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ measurements¹⁾



J.D. Bjorken et al., PRD 80, 075018 (2009)

Summary and Outlook

- B Factories continue to provide significant constraints on dark-matter motivated new physics models
 - Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets
- Belle-II will increase statistics by ~ 100
 - Combined with LHC and direct detection searches, these measurements will provide unique information on the dynamics and flavor structure of new physics



Backup

BaBar Detector

